ANALYTICAL TOOLS FOR RESIDUAL STRESS ENHANCEMENT OF ROTORCRAFT DAMAGE TOLERANCE

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October 1, 2006 – September 30, 2011

Federal Aviation Administration
William J. Hughes Technical Center
Atlantic City International Airport
New Jersey

ANALYTICAL TOOLS FOR RESIDUAL STRESS ENHANCEMENT OF ROTORCRAFT DAMAGE TOLERANCE

J. C. Newman, Jr. and S. R. Daniewicz
Departments of Aerospace & Mechanical Engineering
Mississippi State University
Mississippi State, MS

M. R. Hill
Mechanical and Aerospace Engineering
University of California – Davis
Davis, CA

and

J. Schaff and G. Schneider
Structural Methods and Prognostics
Sikorsky Aircraft Corporation
Stratford, CT

EXPENDITURES (as of January 31, 2007)

	Budget	Expended	Available
FAA	50,000(a)	14,568	35,432
Salaries	9,273	7,905	1,368
Fringe	1,954	313	1,641
Tuition	960	1,205	(245)
Travel	835	1,669	(834)
Subcontracts	21,941	0	21,941(b)
Equipment	0	0	0
Indirect	15,037	3,476	11,561
Total	50,000	14,568	35,432

(a) As of February 8, 2007, MSU received an additional $100K.

(b) Work at UCD and SAC has been done with a lean on future funding.

CRITICAL ISSUES AND CONCERNS

- Funding level ($50K) has been too low to activate and complete tasks under the project (but work is proceeding with in-house funds leveraged against future funding) – resolved as of Feb 8, 2007
- Delays in getting subcontracts with UCD and SAC have added to the slippage in completing the tasks (project task schedule will have to slip by several months)
- Due to availability of 7050, the 7075 alloy has been substituted for the laser-shock peened compact tension specimens and cold-worked hole specimens

TECHNICAL APPROACH

- Phase I – Laboratory Coupons
- Phase II – Rotorcraft Component Applications

PROJECT OBJECTIVES

- Develop and experimental validate analysis methods to predict *residual-stress fields* resulting from life enhancements (such as cold-worked holes, laser-shock peening, and cold-expanded bushings)
- Develop and experimental validate analysis methods to predict *fatigue-crack growth* resulting from life enhancements (such as cold-worked holes, shot and laser-shock peening, and cold-expanded bushings)
- Demonstrate the design tools on rotorcraft components
- Quantify the damage-tolerance benefits for existing and new life-enhancement treatments for rotorcraft applications

RESEARCH ACTIVITIES

- **Rotorcraft Materials, Life Enhancement Processes, and Analysis Verification –**
  Sikorsky Aircraft Corporation (SAC)

- **Coupon Testing & Residual Stress Measurement Program –**
  University of California - Davis (UCD)

- **Analysis Development –**
  Mississippi State University (MSU)

Rotorcraft Materials, Life Enhancement Processes, and Analysis Verification

Jeff Schaff, SAC
George Schneider, Consultant

Major Elements

- Provide guidance on rotorcraft structure life enhancement methods, materials, and structures (Phase 1)
- Provide material and/or test specimens for residual stress measurement and crack growth testing (Phase 1)
- Collaborate with MSU and UCD to assure that analytical models meet needs for rotorcraft structure (Phase 1)
- Perform residual stress and crack growth analyses with SAC codes to compare with USD measurements and MSU FE analyses (Phase 1)
- Provide for technical transfer from MSU and UCD to implement the analytical methods at SAC. (Phase 2)
- Collaborate with MSU to perform detailed analysis of specific rotorcraft components aimed at producing desired life and crack-growth improvements in specific rotorcraft components. (Phase 2)

SAC Schedule Years 1 Through 2

FAA-Analytical-C		Year 1												Year 2											
		O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Task ID	Task Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
C1	Review rotorcraft components, materials & define residual-stress parameters											Time Extension													
C2	Review & define analysis for damage-tolerance modeling					Continue review for length of contract																			
C3	Provide UC Davis 7075 alloy																								
C4	Provide MSU residual stress analyses (SHOTP & CHOLE)											Time Extension													
C5	Fabricate 7075 open hole cold-worked test coupons																								
C6	Residual stress analyses with SHOTP and CHOLE																								
C7	First Annual Report																								
C8	Fabricate 7075 loaded hole cold-worked test coupons																								
C9	Fabricate Ti-6Al-4V β-STOA cold-expanded bushing coupons																								
C10	Superposition crack-growth analyses to support MSU																								
C11	Second Annual Report																								

Cold Work in Rotorcraft Components

Progress

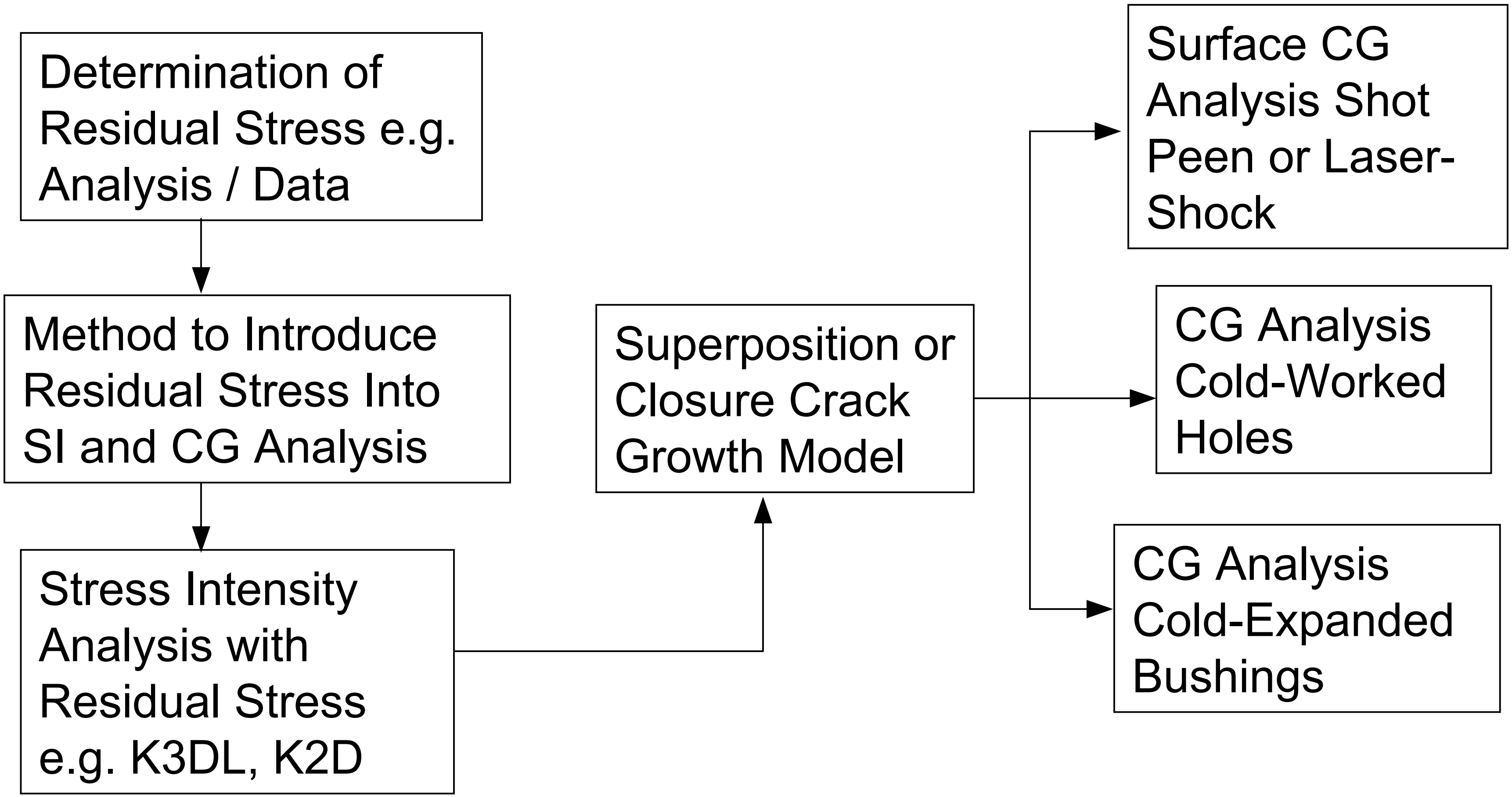
- Conducted brief reviews with Airframe and Rotor Engineers
- Selected Al7075-T6 due to broader use in airframe. Al7050 is limited in application in some thicker frame/beam sections.

- *Airframe Components*
  - Cold working of holes is frequently used in airframe structure
  - Materials: Al7075-T6 (most common), Al7050-T7451, Ti-6Al-4V
  - Thickness: 0.060 to 0.20 inches
  - Hole Diameter: 1/4 and 5/16 inches (1/4 most common)
- *Rotor Components*
  - Cold working of holes is used in a few rotor components
  - MR blade cuff, Ti-6Al-4V β-stoa, Dia ~1.0 in.
  - Swashplate tapped holes, Al7075-T73 forging

Remaining

- Documentation of typical cold-work structure and cold-work specifications to be completed

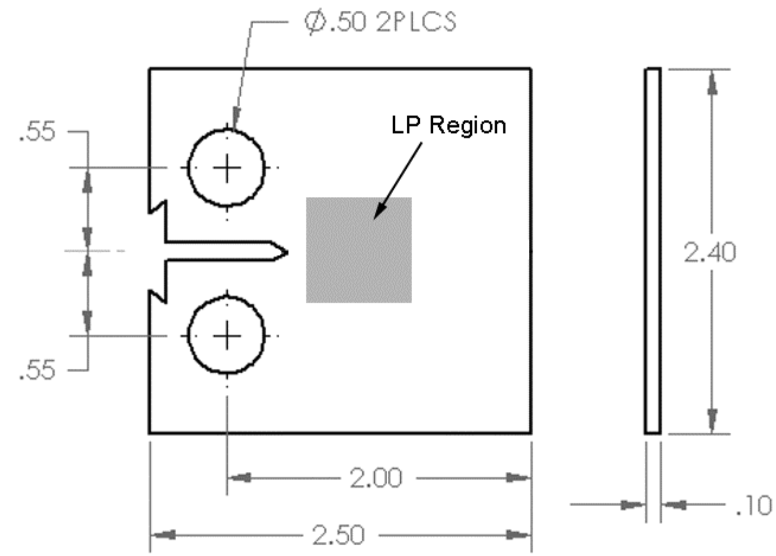
Rotorcraft Analysis Requirements



From DWP Presentation, November 2006

Al7075 Material for Laser Shock Specimens

Laser Shock Test Specimen



- Two Al7075-T6 clad (both sides) plates provided to UCD for laser shot peen C(T) specimens
- Plate dimensions: 24 x 12 x 0.19 inches
- Cladding thickness:
  0.004 - 0.010 inches per side
- Plate Properties:
  Typical: Ftu = 80 ksi, Fty = 70 ksi, E = 10 x10^6 psi

Al7075 Open Hole Cold Work Specimens

Progress

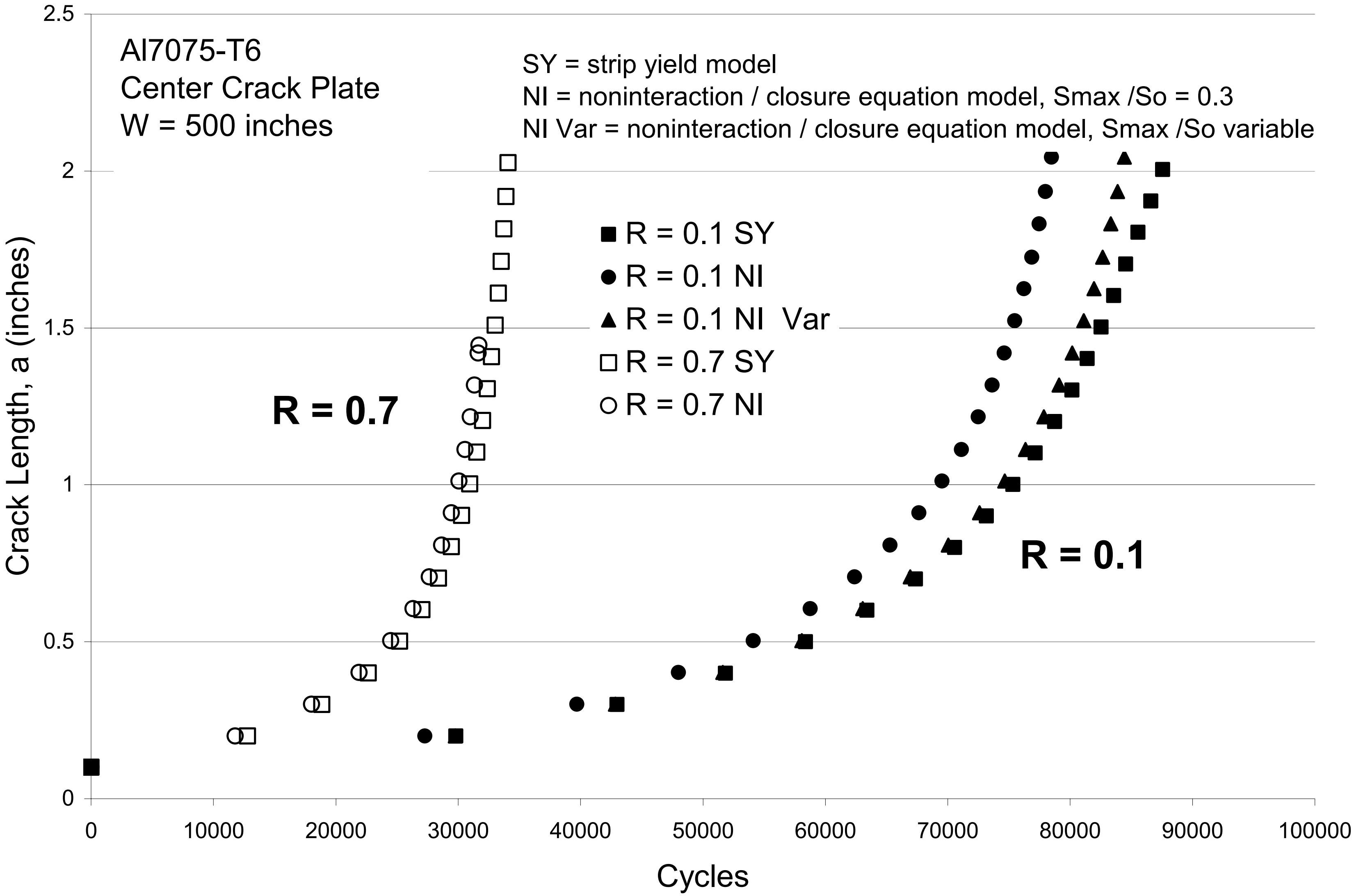
- Identified Al7075-T6 plate material for residual stress and crack growth test specimens
- Plate dimensions: 12 X 48 X 0.19 inches, Clad
  12 X 48 X 0.08 inches, Clad

Test plan initiated -- Reviewing previous MSU/SAC CW test data and literature on effects of cladding.

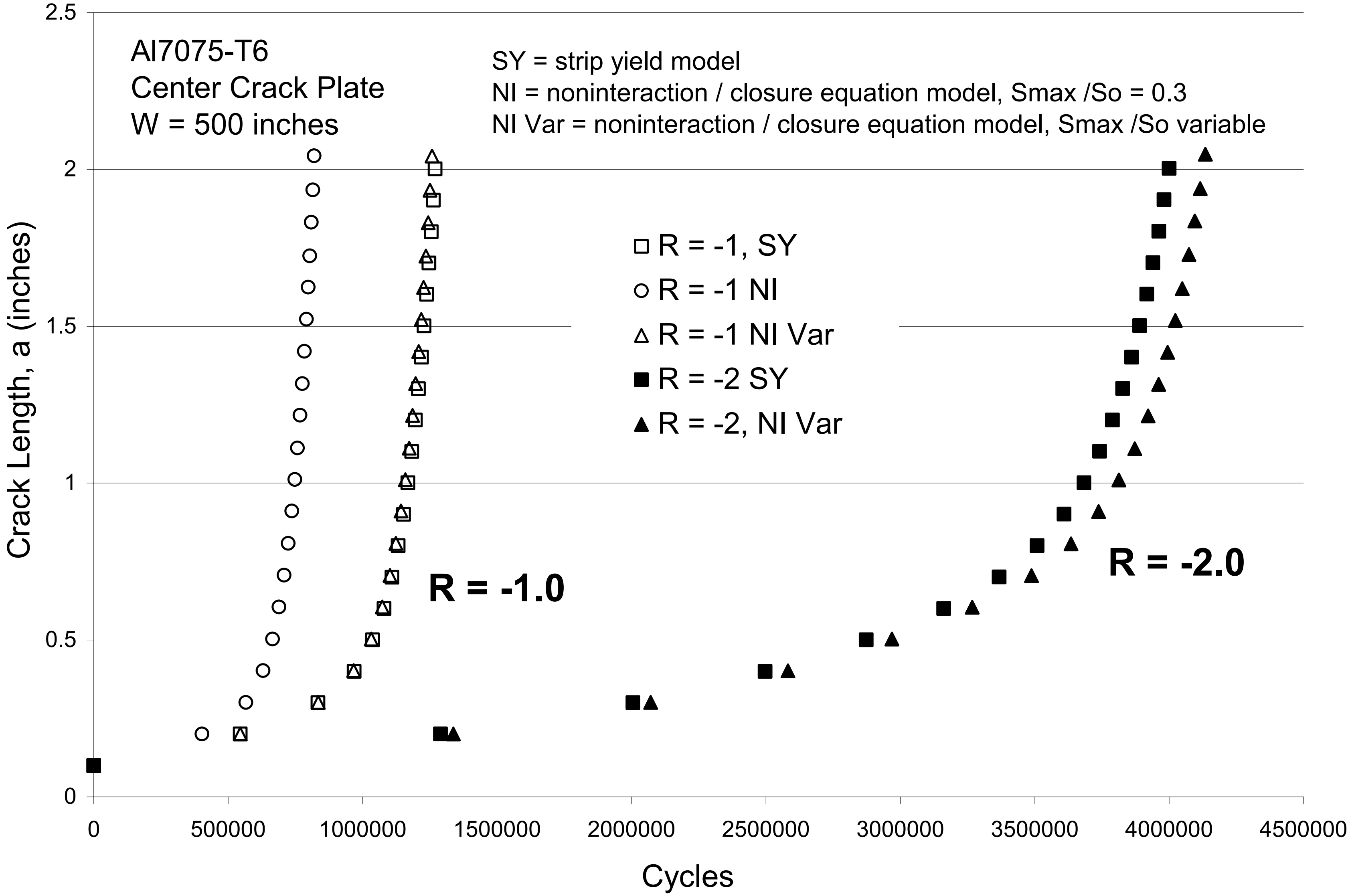
Remaining

- Stress intensity analysis with NASGRO for cold work and applied loads to define cold work levels (reaming) and initial crack (EDM) size
- Complete test plan
- Fabricate residual stress specimens
- Fabricate crack growth test specimens

Evaluation of NASGRO CG Models (1)



Evaluation of NASGRO CG Models (2)



SAC Future Plans

- **Near Future**
  - Complete review and documentation on rotorcraft residual stress parameters for cold-worked holes
  - Analyze stress intensities for cracks at open cold-worked holes, define test specimens, and fabricate Al7075-T6 test specimens
  - Provide MSU with CHOLE and SHOTP analyses
  - Compare CHOLE4 cold-work residual stress analysis with MSU FE analysis
- **Future**
  - Analyze stress intensities for cracks at loaded cold-worked holes, define test specimens, and fabricate loaded hole Al7075-T6 test specimens
  - Fabricate Ti-6Al-4V cold-expanded bushing specimens
  - CHOLE4, SHOTP and superposition CG analysis to support MSU

Coupon Testing & Residual Stress Measurement Program

Michael R. Hill, MAE, UCD
John VanDalen, MAE, UCD

Major Elements

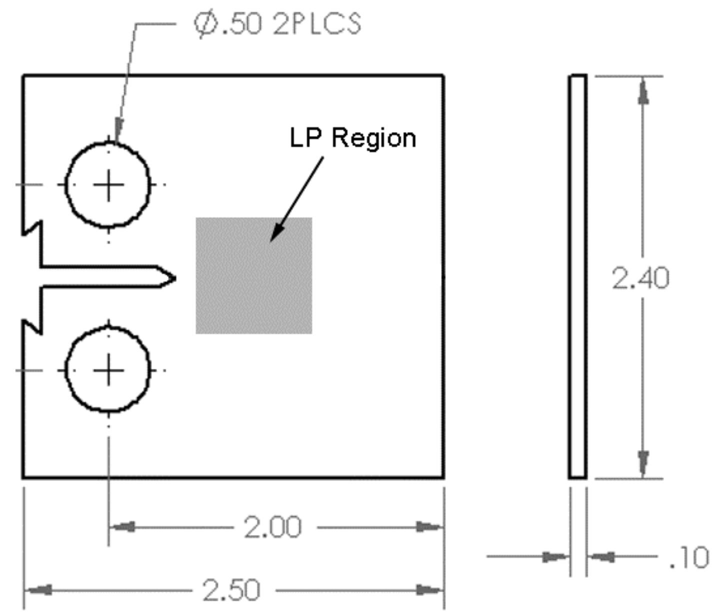
- **Residual stress and crack growth in laboratory coupons**
  - C(T) coupons (laser-shock peened)
  - Open hole thin coupons (CW)
  - Open hole thick coupons (CW)
  - Cold expanded bushing coupons
  - Surface crack coupons (shot or laser-shock peened)
- **Provide transfer of existing data related to laser-shock peening**
- **Provide consulting and laboratory testing to support rotorcraft component evaluations**
  - Details of support to depend on components evaluated
  - Provide residual stress measurement capability and expertise
  - Provide fatigue testing capability and expertise

UC Davis Schedule Years 1 and 2

FAA-Analytical-B		Year 1												Year 2											
		O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Task ID	Task Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
B1	C(T) coupons residual-stress measurements																								
B2	C(T) coupons fatigue-crack-growth data																								
B3	Open hole coupons residual-stress measurements																								
B4	Open hole coupons fatigue-crack-growth data																								
B5	First Annual Report																								
B6	Transfer laser-shot data to SAC																								
B7	Loaded hole coupons fatigue-crack-growth data																								
B8	Cold-expanded bushing coupons residual-stress data																								
B9	Cold-expanded bushing coupons crack-growth data																								
B10	Second Annual Report																								

7075-T6 C(T) Crack Growth Tests [B1,B2]

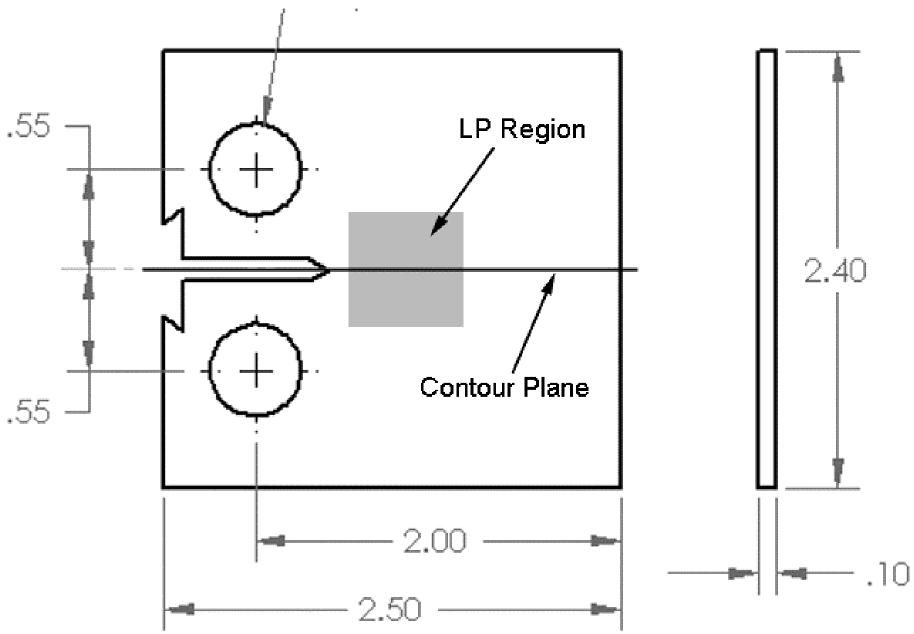
- **Useful starting point**
  - SIF well-defined
  - One-dimensional crack
  - Significant residual stress (RS) effects from laser peening (LP)
- **Coupons per ASTM E647**
  - B = 0.15 in, W = 2.0 in
  - Material provided by SAC
  - Fabrication sourced by UCD
- **Laser peening to be applied by Metal Improvement Company (MIC)**
  - Small region in front of crack path
  - Expect through-thickness compression
- **Up to three sets of coupons**
  - As-machined (no LP)
  - Low stress ratio (R = 0.1)
  - High stress ratio (R = 0.5)



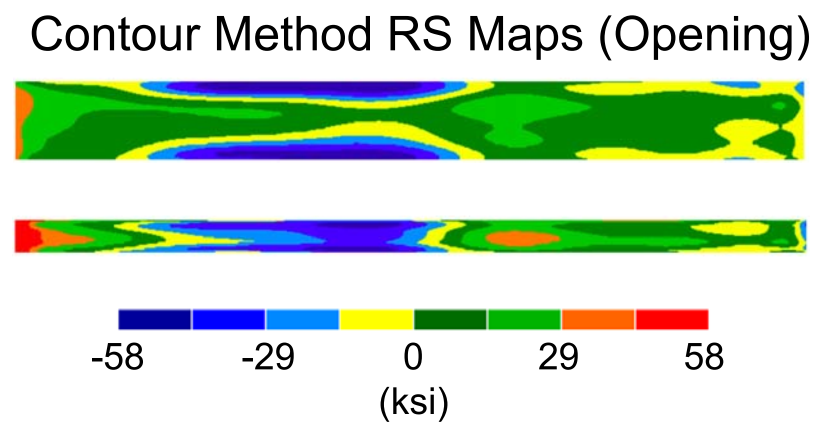
C(T) Coupon

B1: 7075-T6 C(T) Coupons, RS Measurement

- **Objective:**
  - Measure RS distribution induced into C(T) coupons by LP along the plane of the crack using contour method.



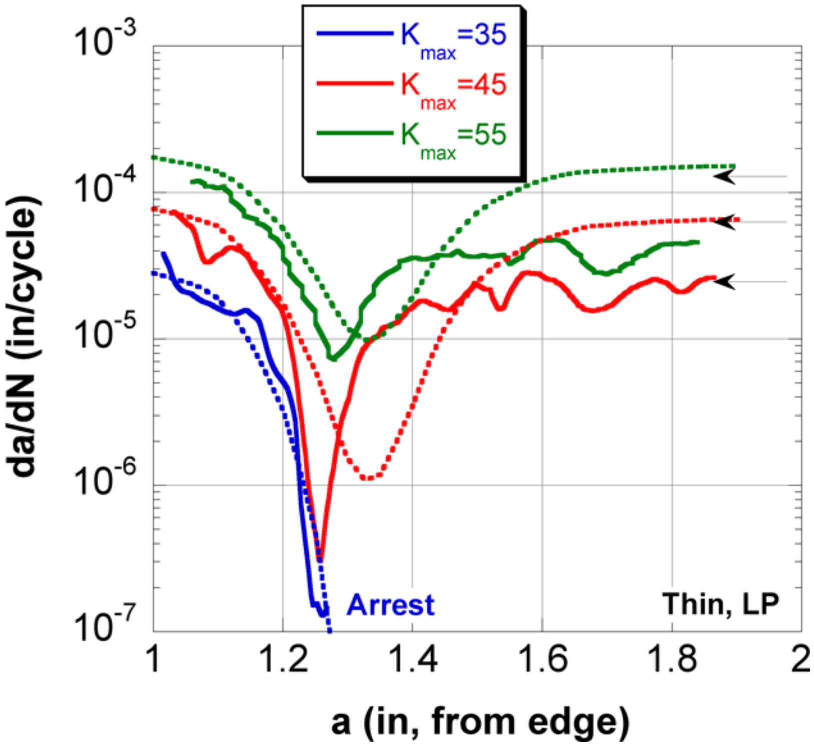
C(T) coupon indicating contour plane

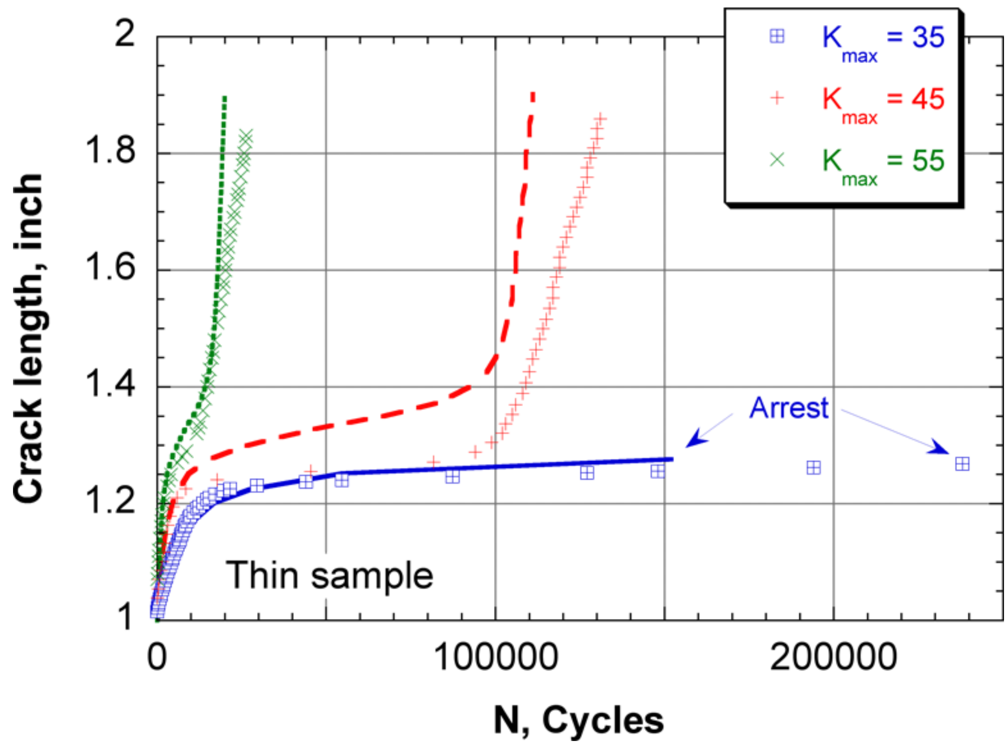


Results from earlier work in LP β-STOA Ti6Al4V

B2: 7075-T6 C(T) Crack Growth Data

- **Objective:**
  - Determine effect on fatigue crack growth (FCG) rate due to LP. Coupons will be tested at constant ΔK.

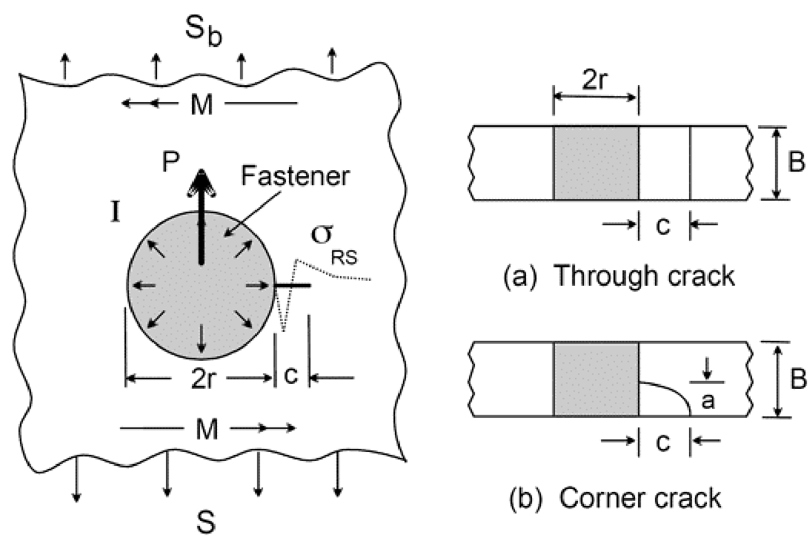




Results from earlier work in LP β-STOA Ti6Al4V

7075-T6 Cold-Expanded Hole Coupons [B3,B4,B7]

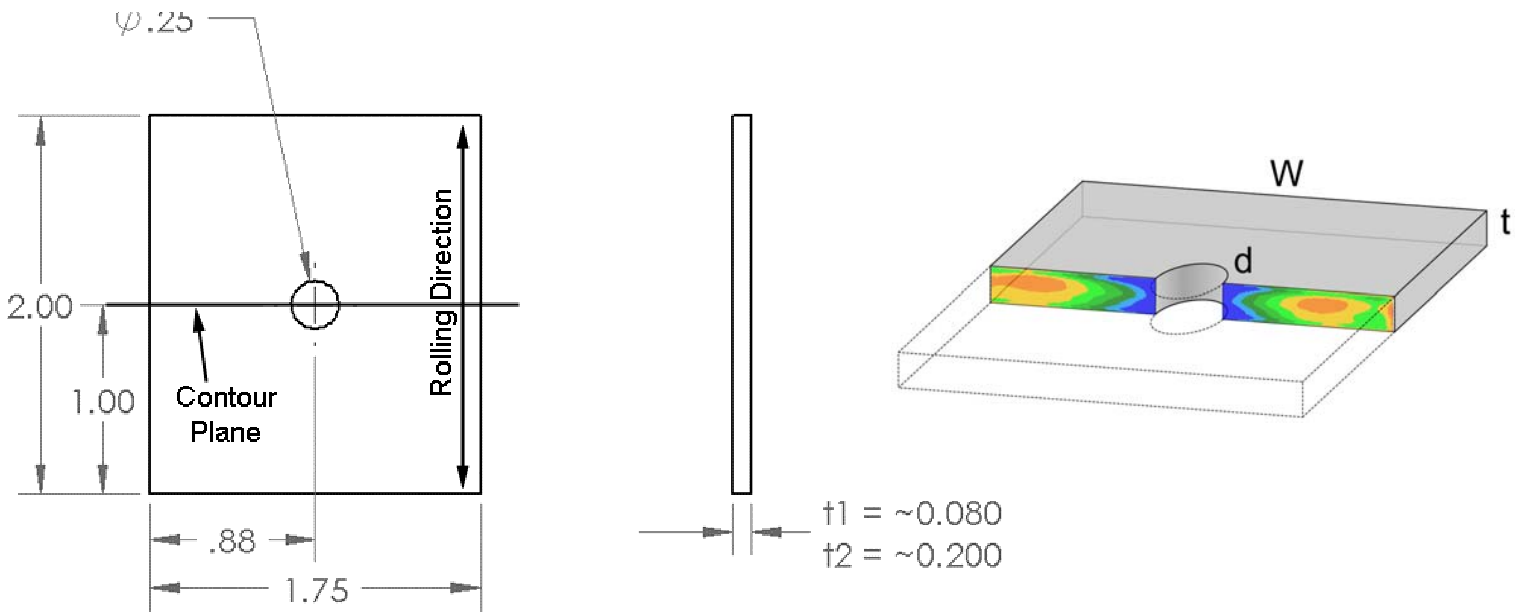
- Through-thickness and corner cracks will be studied for two thicknesses (e.g., B = 0.08 in and 0.2 in)
- Open-hole and loaded-hole setups will be evaluated.
- Initial flaws will be made by EDM after cold-hole expansion (CHE) process
- Material, coupon fabrication and CHE will be provided by SAC
- Amount of RS from CHE is controlled by varying initial reaming size, while holding the final hole size constant.
- Constant-amplitude loading will be applied for determining FCG



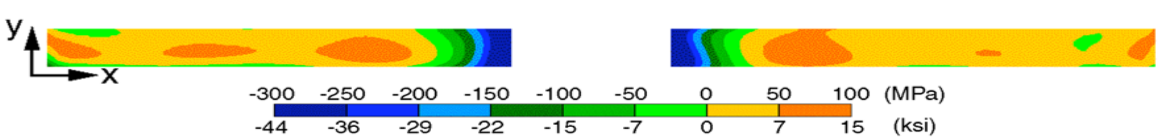
Loaded-hole coupon with through-thickness and corner crack.

B3: Open-Hole Coupons, RS Data

- **Objectives:**
  - Measure RS from cold-hole expansion on crack plane
  - Use measured RS to develop cold-expansion parameters



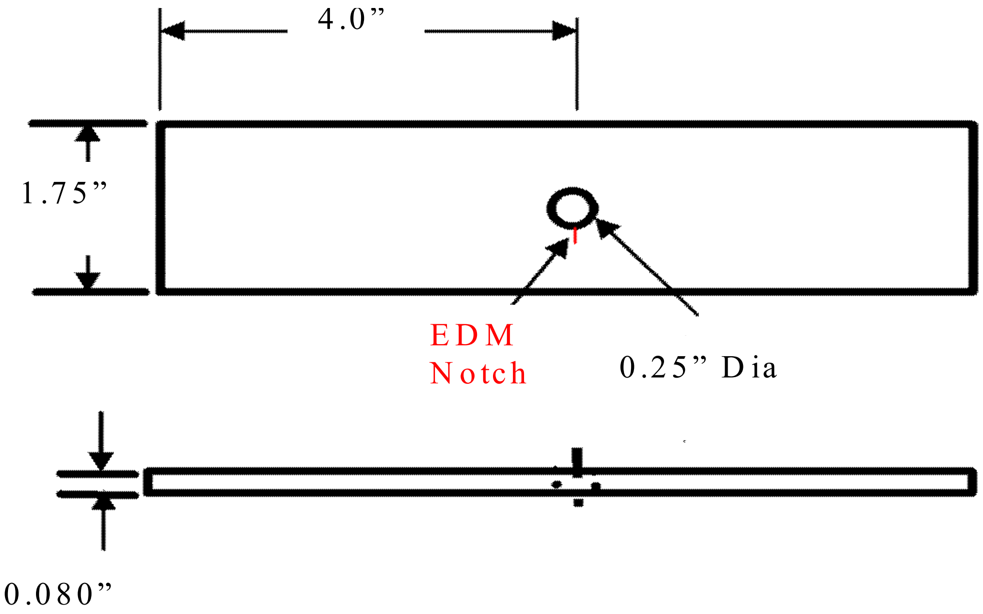
Open-Hole RS Coupons showing contour plane



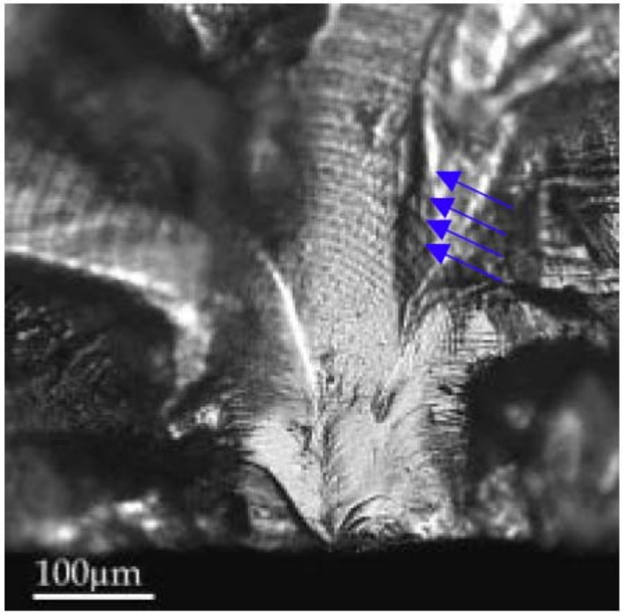
Example CW Hole Contour Results

B4: Open-Hole Coupons, FCG Data

- **Objectives:**
  - Design coupons based on RS from B3 and LEFM or FASTRAN
  - Obtain FCG rates for through-thickness and corner cracks in open-hole coupons with and without CHE
  - Develop method for tracking growth of corner cracks



Marker loading: DSTO-TR-1477 (2003)



Example: Open-hole coupon used previously by SAC and MSU. Coupons for this program will be similar.

UCD Future Plans

- **Near Future**
  - C(T) residual stress measurements
  - C(T) crack growth measurements
- **Future**
  - Open hole coupon design
  - Open hole residual stress measurements
  - Open hole tests with thin material
  - Open hole tests with thick material

Analysis Development

Jim Newman, AE, MSU
Steve Daniewicz, ME, MSU
Shakhrukh Ismonov, ME, MSU

Major Elements

- Develop methods to calculate ***residual stresses*** for various life-enhancement treatments (cold-working and cold-expanded bushings for fastener-loaded holes) using three-dimensional finite-element methods and compare measurements made at UCD and computed CHOLE (proprietary) result from SAC. (Phase 1)

- Develop methods to calculate ***fatigue-crack growth*** for various life-enhancement treatments (peening, cold-working and cold-expanded bushings for fastener-loaded holes) using linear superposition and nonlinear treatment with FASTRAN and compare with measurements from UCD and results from SAC. (Phase 1)

- Provide for technical transfer to implement the analytical methods at SAC. (Phase 2)

- Collaborate with SAC to perform detailed analysis of specific rotorcraft components aimed at producing desired life and crack-growth improvements in specific rotorcraft components. (Phase 2)

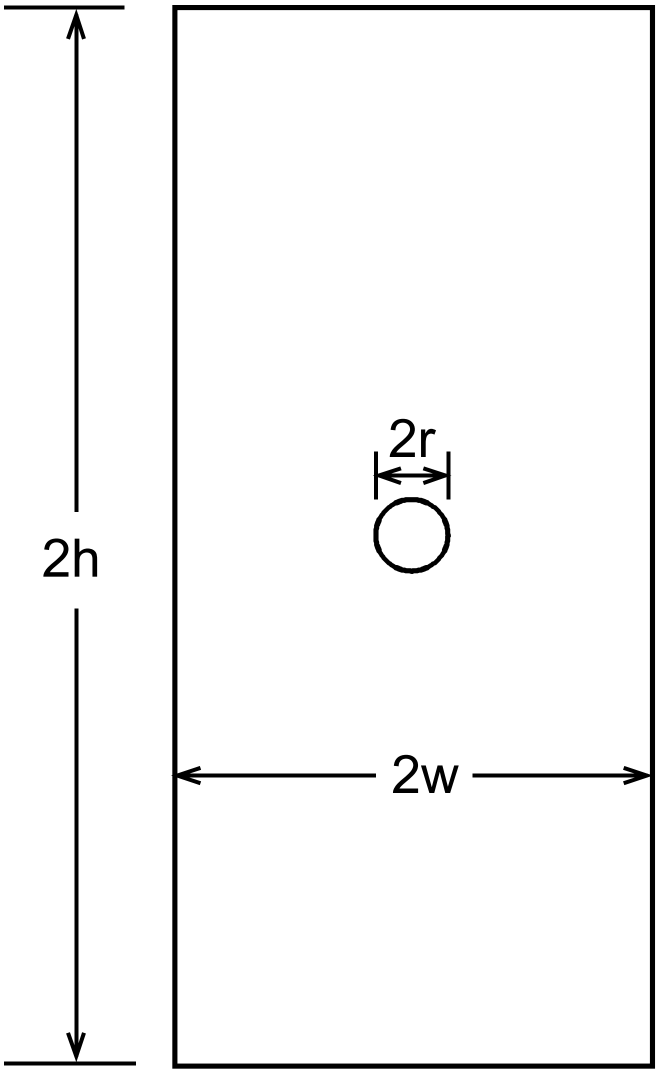
MSU Schedule Years 1 Through 3

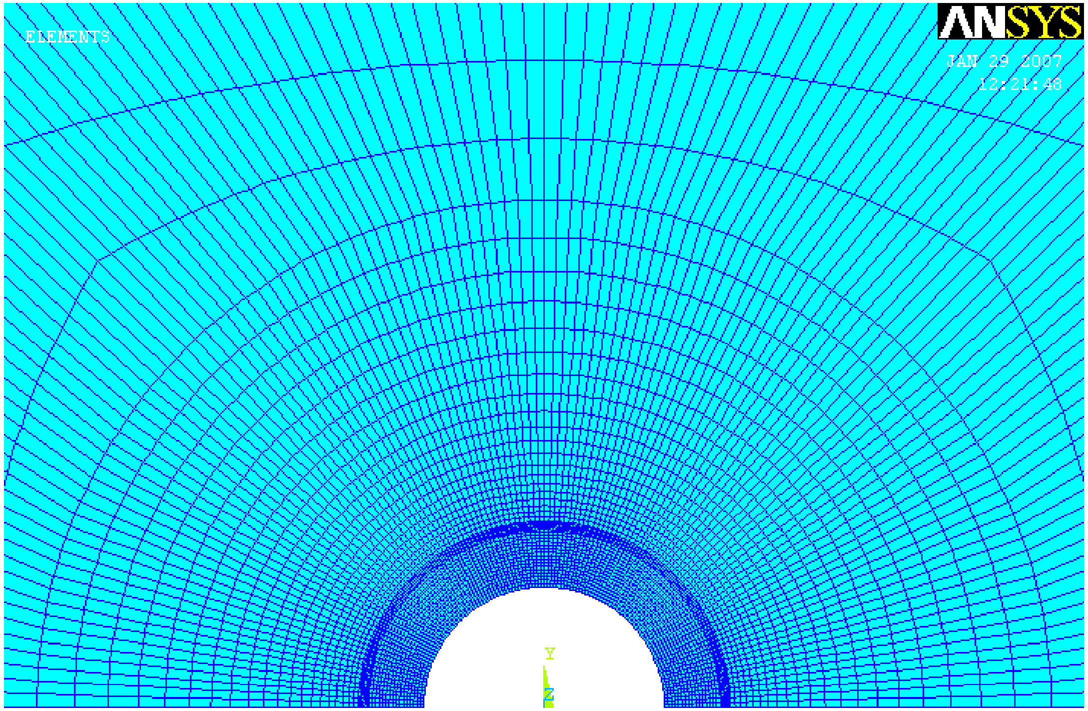
FAA-Analytical-A		Year 1												Year 2												Year 3											
		O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Task ID	Task Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
A1	Literature survey on residual stress enhancements																																				
A2	3D SIF table for FASTRAN																																				
A3	3D FEA of cold-working process																																				
A4	K3DL for SIF for 3D cracks																																				
A5	K2D for SIF for 2D cracks																																				
A6	First Annual Report																																				
A7	FCG analyses of 7050 alloy																																				
A8	Improved FASTRAN for cold-worked holes																																				
A9	SIF for fastener-loaded holes																																				
A10	Second Annual Report																																				
A11	Superposition method implemented into FASTRAN																																				
A12	Superposition method and FASTRAN on CW holes																																				
A13	Stress analysis on cold-expanded bushings																																				
A14	FCG analyses of of Ti-6Al-4V β-STOA alloy																																				
A15	Third Annual Report																																				

Accomplishments

- **Literature review being finalized**
  - Four life enhancement processes: shot-peening, laser-peening, cold expansion of holes and cold-expanded bushings
  - Recently published research related to numerical and analytical methods to estimate residual stresses
- **Previous FAA grant finite-element analyses of cold-working replicated**
  - Analysis was conducted with ANSYS Release 10.0A1
  - 2D simulation includes cold expansion of hole, reaming and slotting processes
  - Hole expansion process simulated by uniform radial displacements at the hole surface
  - Reaming and slotting was performed using Element Kill command to deactivate a layer of elements at the hole surface
  - Multi-linear isotropic hardening material behavior was used for the 7075-T6 aluminum alloy specimen
- **FASTRAN**
  - Crack-growth analyses compared to NASGRO results from SAC
  - 3D stress-intensity factor table-lookup under development

Two-Dimensional (2D) Model

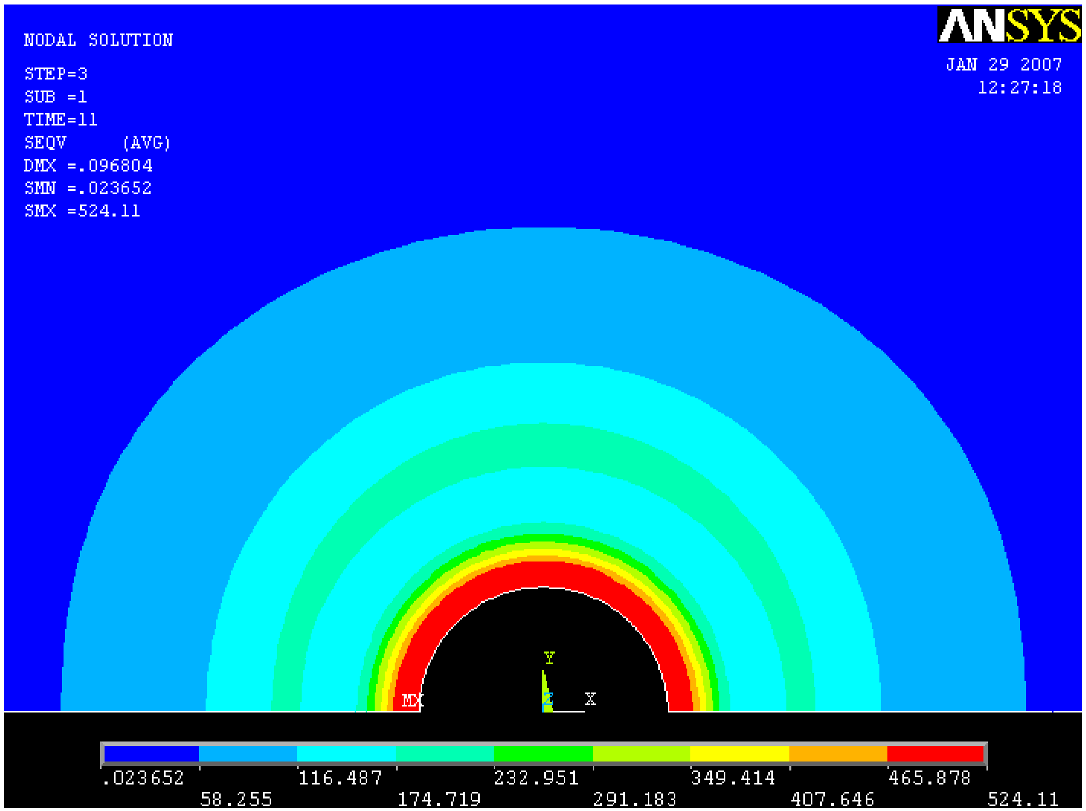


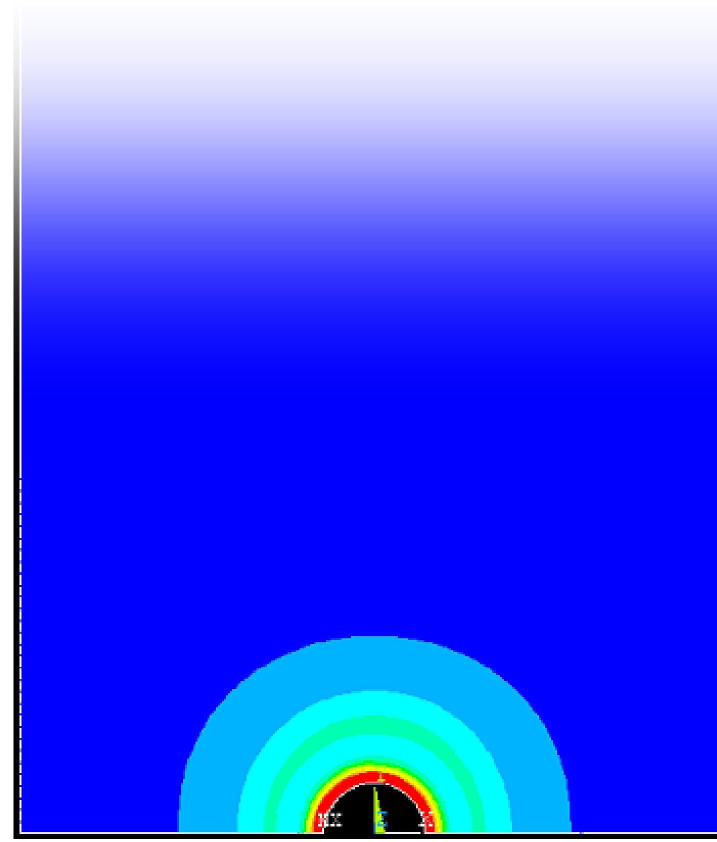


Local element mesh pattern at hole

Residual Stress Contour during Cold Working

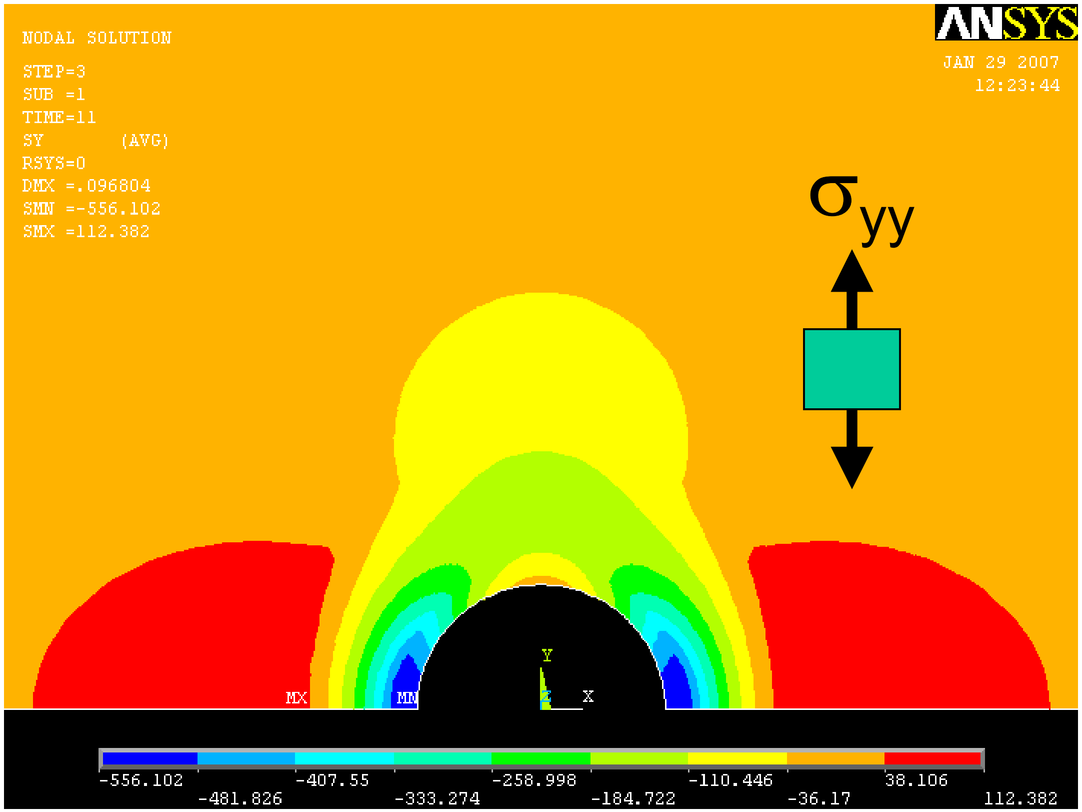
Von-Mises residual stress contour at the maximum uniform cold-expansion level (prior to reaming)

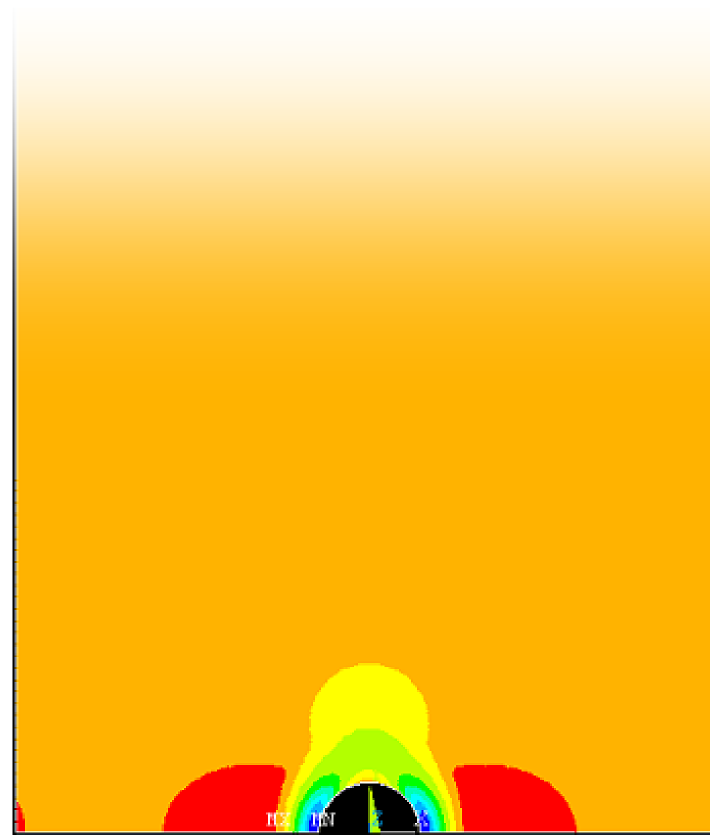




Normal Residual Stress (σ_{yy}) Contour

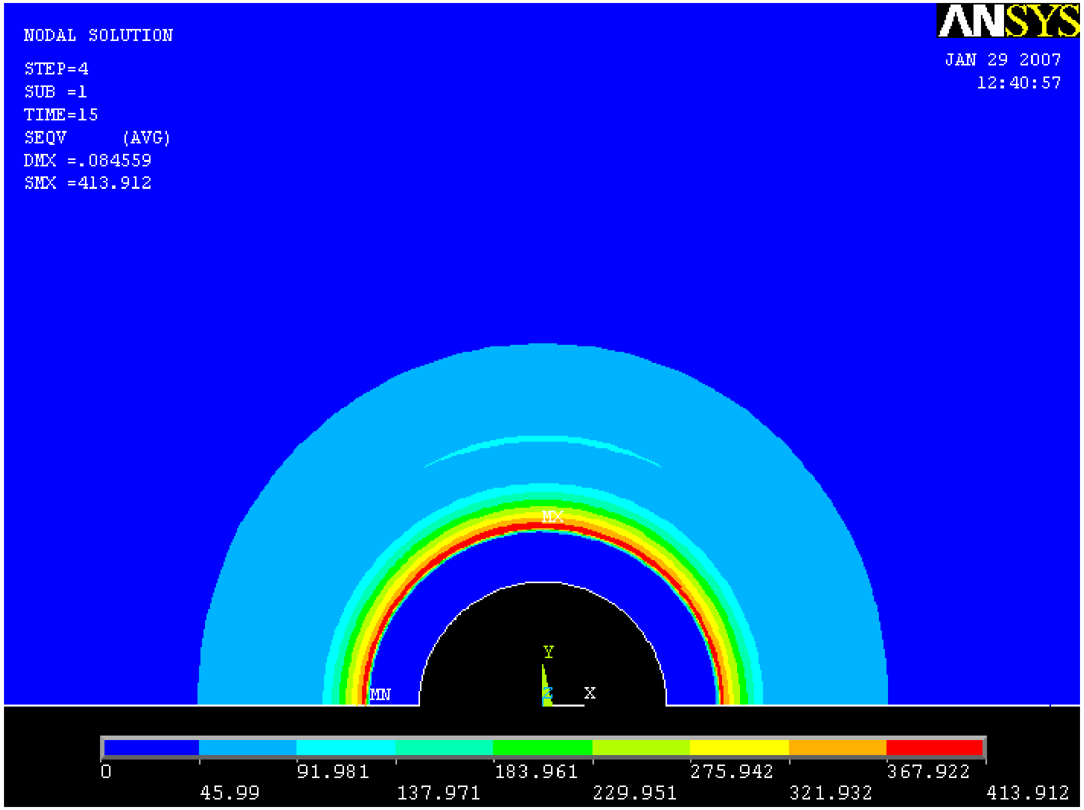
Normal residual stress contour after unloading from uniform cold expansion (prior to reaming)

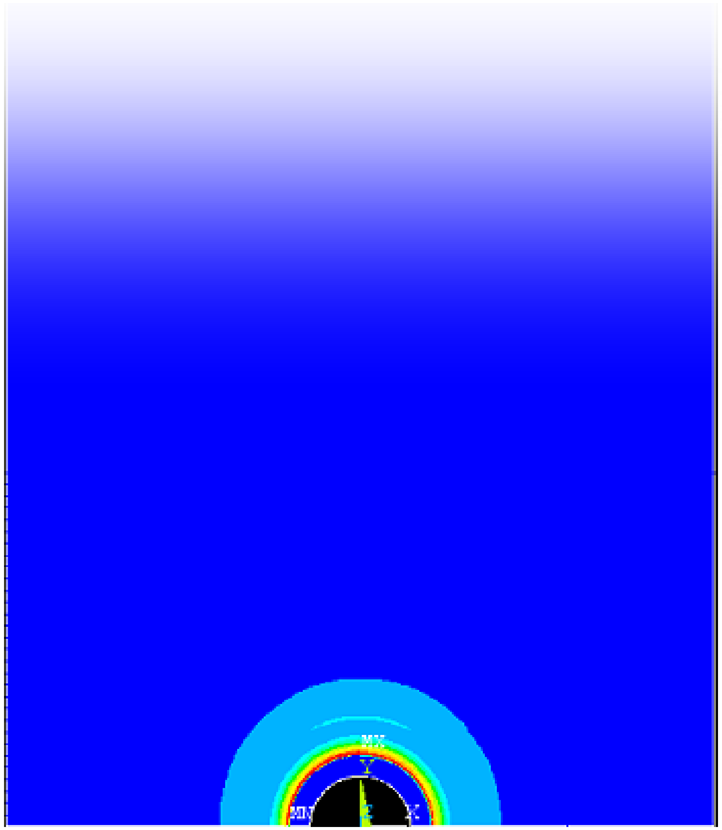




Residual Stress Contour after Reaming

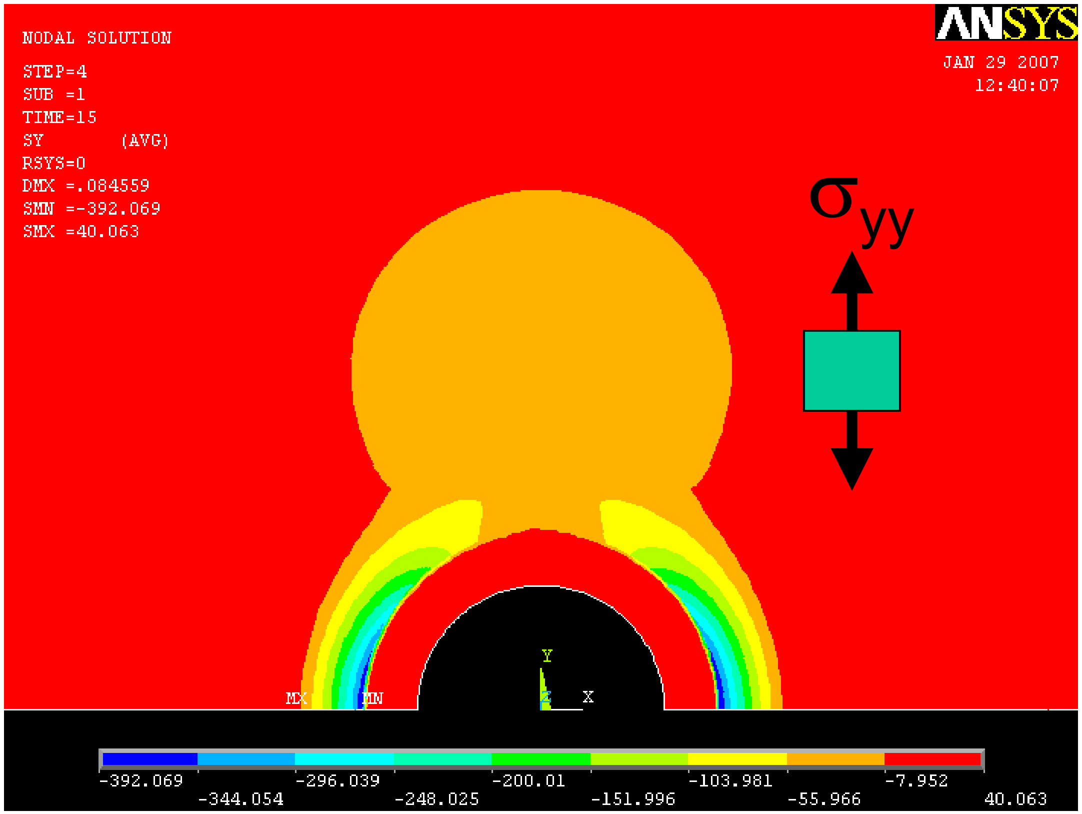
Von-Mises residual stress contour after reaming





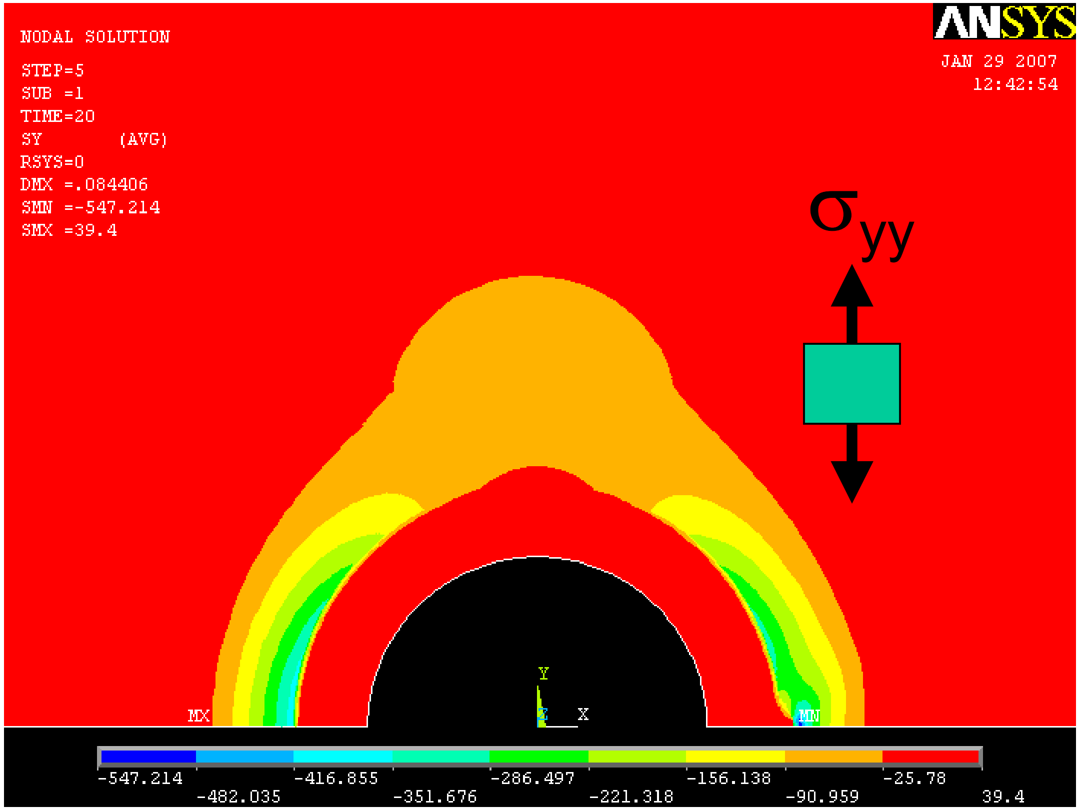
Normal Residual Stresses after Reaming

Normal residual stress contour after reaming

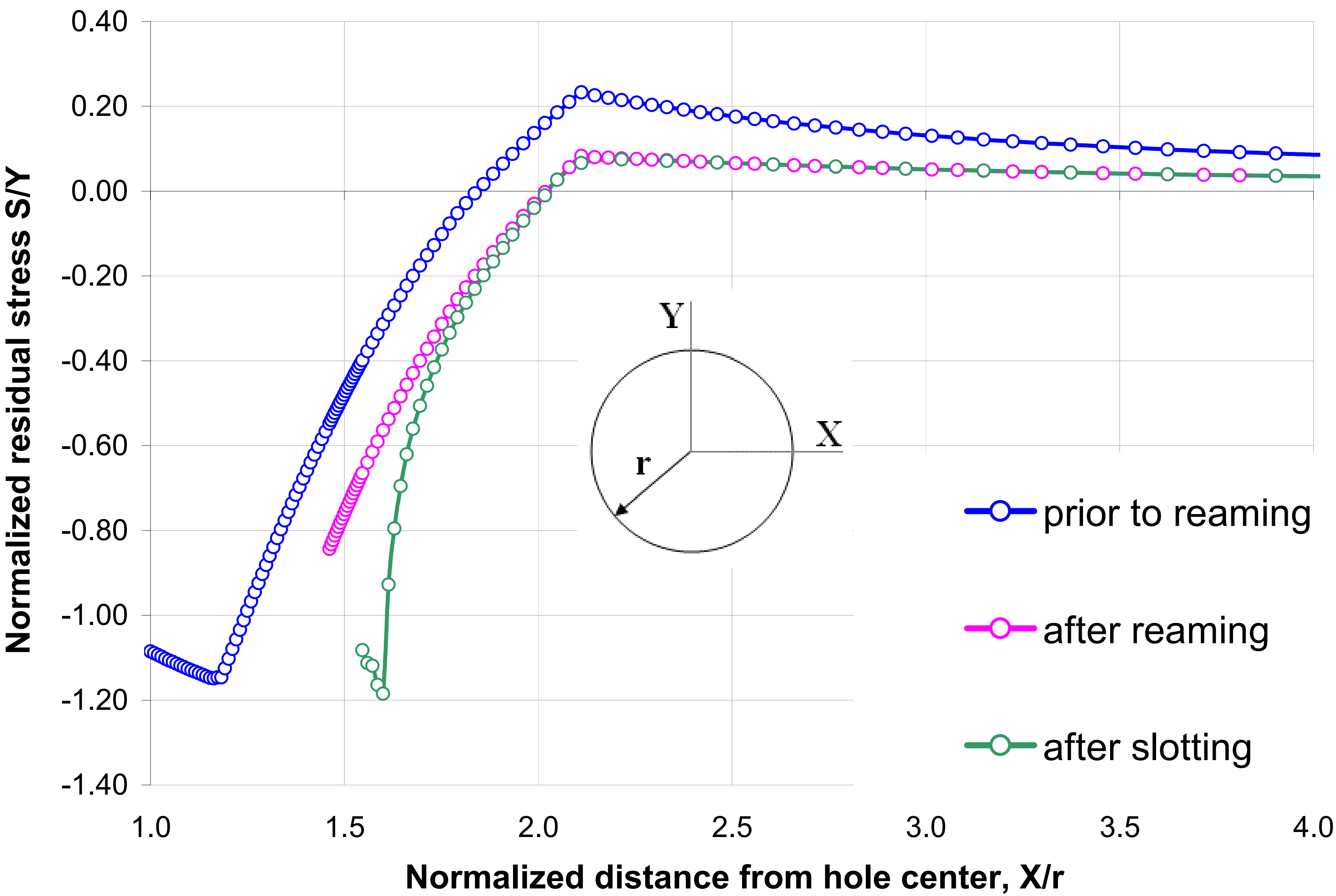


Normal Residual Stresses after Slotting

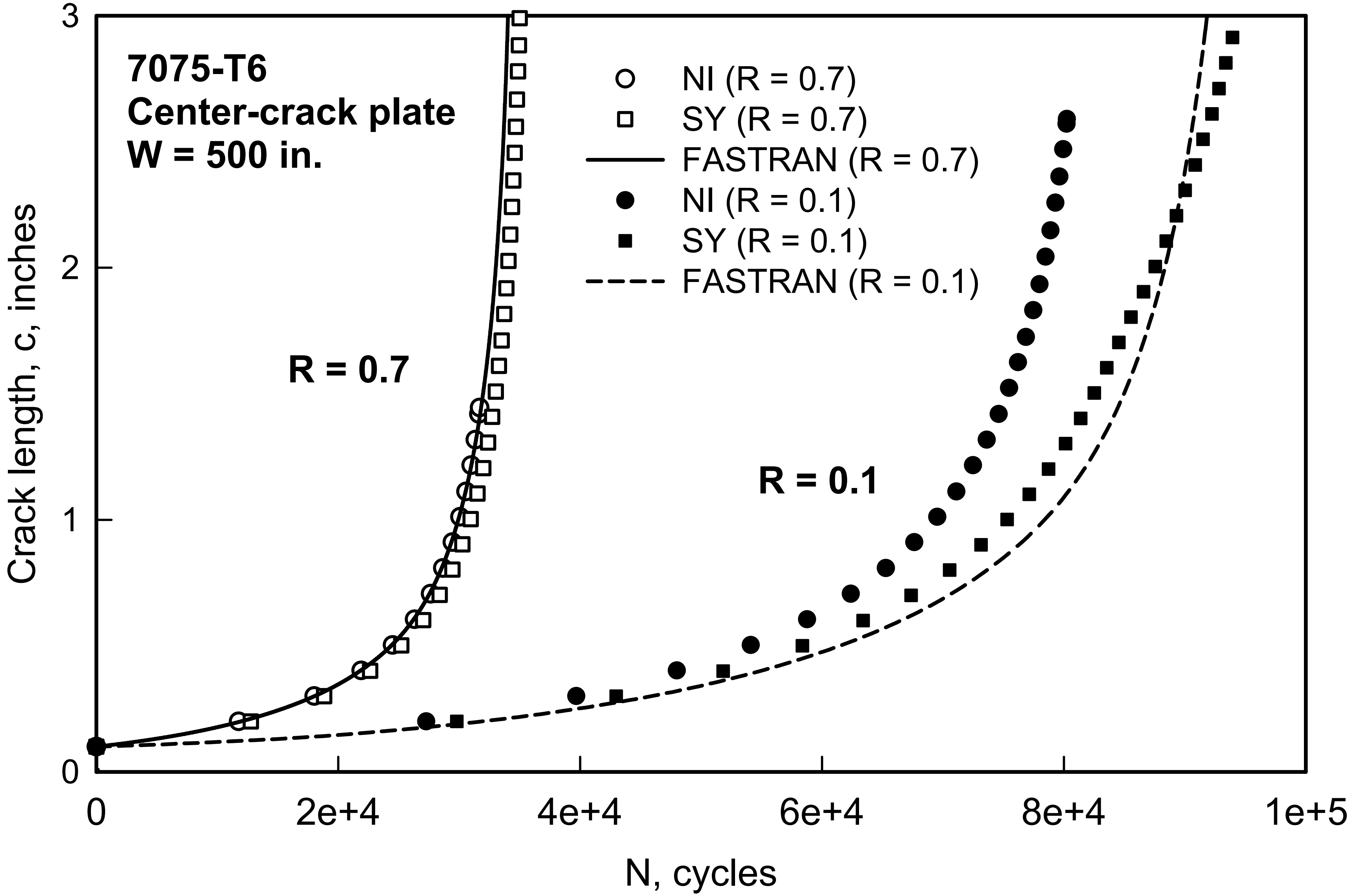
Normal residual stress contour after slotting



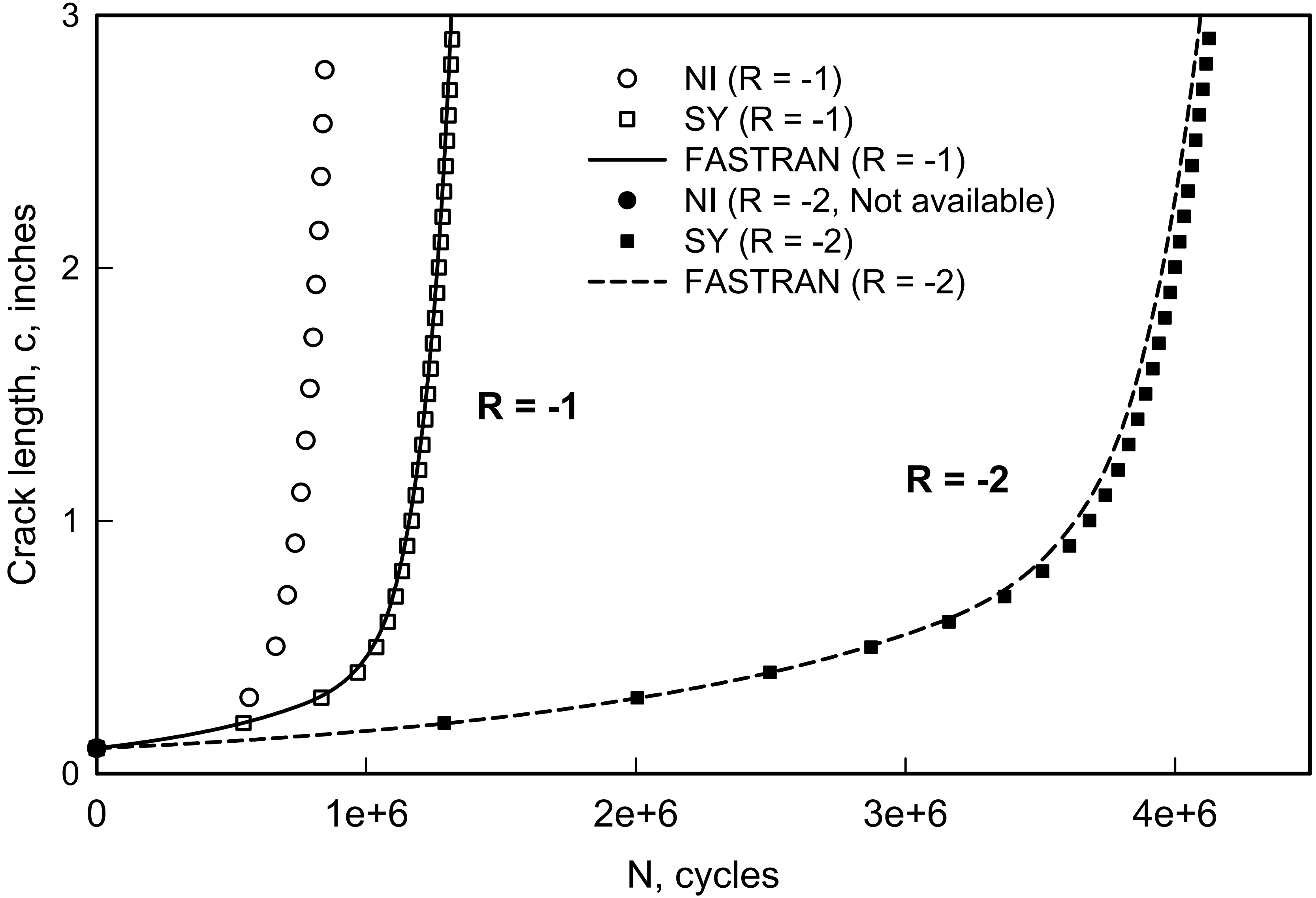
Residual Stresses from Cold Working



NASGRO and FASTRAN Comparisons (1)



NASGRO and FASTRAN Comparisons (2)



MSU Future Plans

- **Near Future**
  - 3D elastic-plastic finite-element analyses will be initiated to study variation of residual stresses through the thickness, including frictional effects
  - 3D stress-intensity factor table-lookup will be implemented into FASTRAN
- **Future**
  - Perform finite-element analyses to compute local stresses in fastener-loaded holes
  - Computed residual stresses will be compared with cold-work hole measurements made at UCD
  - FEA of local stresses produced by cold-expanded bushings
  - Improved Green's function will be developed for concentrated forces on crack in compact specimen